EFFECT OF THE END AND SIDE CONNECTIONS TO THE HOLLOWCORE CONCRETE FLOORING SYSTEMS IN FIRE

Jeremy Chang
Assistant Lecturer, PhD (Canterbury), University of Canterbury, New Zealand
Andrew H. Buchanan*
Professor, PhD (UBC), University of Canterbury, New Zealand
Rajesh P. Dhakal
Senior Lecturer, PhD (Tokyo U.), University of Canterbury, New Zealand
Peter J. Moss
Associate Professor, PhD (London), University of Canterbury, New Zealand

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ABSTRACT

This paper analytically investigates the structural performance of hollowcore concrete floor systems in fire comparing several connection details which are verified to provide better seismic performance. The results show that the connections which are beneficial to the system's seismic performance are not always suitable for the fire performance, and rotationally rigid connections provide better fire resistance than rotationally flexible connections.

1. INTRODUCTIONS

Hollowcore concrete slabs are precast, pre-tensioned concrete units. They are typically 1.2 m wide with full length voids, and their thickness is usually between 200 and 400 mm, and depending on the design requirements. Hollowcore floor systems consist of adjacent hollowcore concrete slabs with or without a layer of in-situ reinforced concrete topping. Using hollowcore concrete floor systems in multi-storey buildings is common in many countries, but the structural behaviour of such systems under fire exposure is not easy to predict due to the complex geometry, composite construction, and a wide range of possible support conditions.

The aim of this study is to investigate the fire performance of hollowcore floor slabs with different connection details between the hollowcore units and their reinforced concrete supporting beams. The importance of connections between the hollowcore floor systems and perimeter beams on the structural performance in earthquakes has been found in several studies [1,2,3]. The collapse of hollowcore units can be caused by poorly designed connections together with incompatibility between the ductile seismic resisting frame and the brittle

* Corresponding author - Departament of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand. E-mail: andy.buchanan@canterbury.ac.nz

hollowcore flooring system during earthquakes. In recognition of this effect, new details for the connection of hollowcore floor units to reinforced concrete supporting beams were introduced in the 2006 version of the New Zealand Concrete Standard NZS3101 [4] to improve seismic performance. The new details require the designers to demonstrate that the hollowcore units can accommodate the difference in rotations between the beam and supports in earthquakes. There are two ways to achieve this: either reduce the rotational fixity between the ends of the hollowcore units and their seating beams, or strengthen the end region of the units to eliminate the rotational incompatibility between the end beams and the hollowcore units. These two methods are reflected by the end connections shown in Figure 1 (b) and (c), proposed by Lindsay [5] and MacPherson [6] respectively. The side connection detail shown in Figure 2 (b) can withstand a greater difference in rotations between the beam and floor slab than the usual connection in Figure 2 (a). However, the fire performance of these new connection systems is yet to be determined.

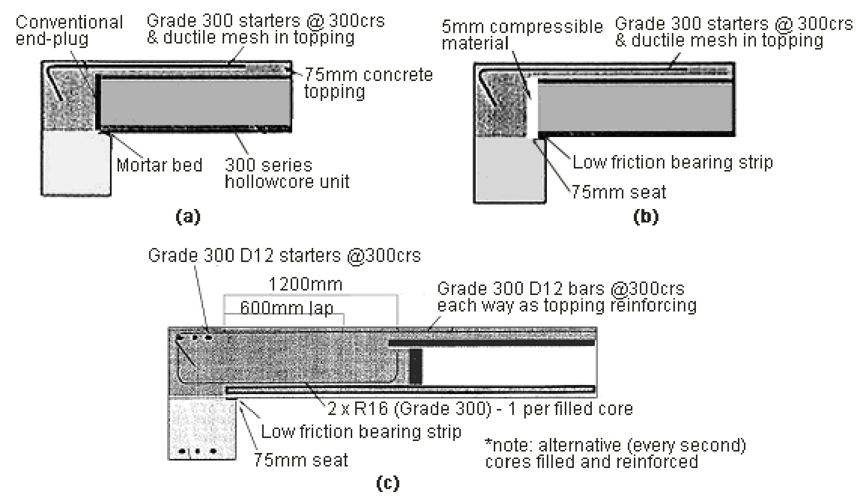

Figure 1: Modelled end connections (a) “simple end connection” [3] (b) “gapping end connection” [5] (c) “non-gapping end connection” [6]

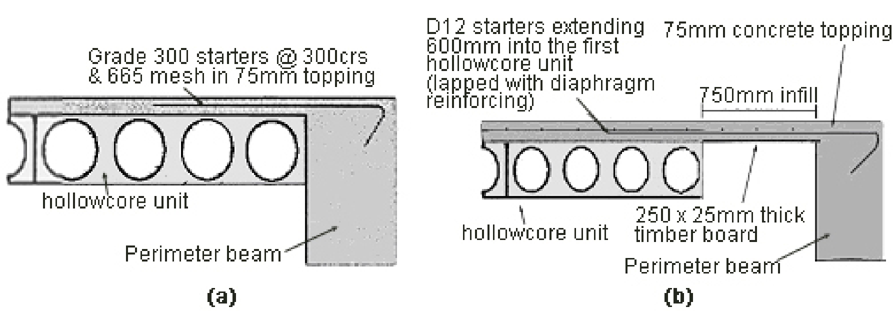

Figure 2: Modelled slab-side beam connections (a) “no-infill side connections” (b) “infill side connection” [5]

The structural performance of hollowcore floor systems in fire can be affected by many factors, such as steel cover, size and shape of the member, aggregate type, reinforcement type and load intensity, but Carlson et al. [7] have shown that the axial restraint is often more influential than these other factors. Axial restraint can prevent tension-induced cracks in concrete from opening, hence enhancing the effect of aggregate interlocking [8], it also limits the growth of lateral cracks and reduces the likelihood of slipping of prestressing strands, and therefore increases the fire resistance of hollowcore floor systems [9]. Hence, good design of connections between floor systems and perimeter beams is important for the performance of structures both in earthquakes and in fire.

2. STUDIED SPECIMENS

The dimensions of floor subassemblies in real buildings are too big for conducting full scale fire tests; therefore, computer simulations are carried out as virtual ISO 834 [10] standard fire tests in lieu of conducting experiments in the laboratories. The failure criterion of the slab is taken as either the collapse of the slab, or the time when the maximum deflection exceeds 3.3% of the span length, as in a standard fire test.

The studied specimen is 12.2m long with a floor slab exposed to the ISO fire from underneath. The width of the modelled slab in all cases was 10.2 m, consisting of eight units if the last unit is adjacent to the side beams as shown in Figure 2(a), or seven units if there is a concrete infill panel between the last unit and the side beams as shown in Figure 2(b). The floor is made from 300 mm thick hollowcore units (300Dycore) with a 75 mm topping reinforced at mid-height by a mesh of 5.3 mm bars with 150 mm spacing in both directions. The floor slab is supported on 450mm wide by 750mm deep normal strength reinforced concrete beams which are connected to four 3.5m long and 750 by 750mm square reinforced concrete columns at their mid-height as shown in Figure 3. The columns are restrained against displacement at both the top and bottom ends. The modelled subassembly is based on the specimen tested for studying the seismic performance of the connections by MacPherson [6]. The load applied onto the floor slab including the self-weight is 8.0kPa, which is equal to 40% of the flexural load capacity under ambient conditions.

Three types of end connections are studied in this paper. The end connection shown in Figure 1(a) is referred to as a “simple end connection” and has the hollowcore units simply sitting on the end beam. The linkage between the units and the end beam is established via the extended starters in the topping slab and friction at the mortar bed seating. This end connection is not recommended for seismic designs, and NZS 3101:2006 [4] suggests using one of the two types of end connections, which are the “gapping end connection” shown in Figure 1(b) and the “non-gapping end connection” shown in Figure 1(c). The “gapping end connection” has the hollowcore units located 5mm away from the face of the end beam to provide rotational freedom, and the “non-gapping” end connection” has the hollowcore units strengthened by filling every second core with reinforced concrete for 900mm from the ends.

This study also investigates two types of connections to the side beams. The side connection in Figure 2(a) is referred to as the "no infill" side connection and has the last hollowcore unit immediately adjacent to the side beam. This is not recommended for seismic designs. The connection shown in Figure 2(b) is referred to as the "infill" side connection, with a cast-in situ reinforced concrete infill slab between the last hollowcore unit and the side beam to overcome the incompatibility between the displacement of the side beams and the slabs during earthquakes. An extreme scenario where the side beams are not included is also studied.

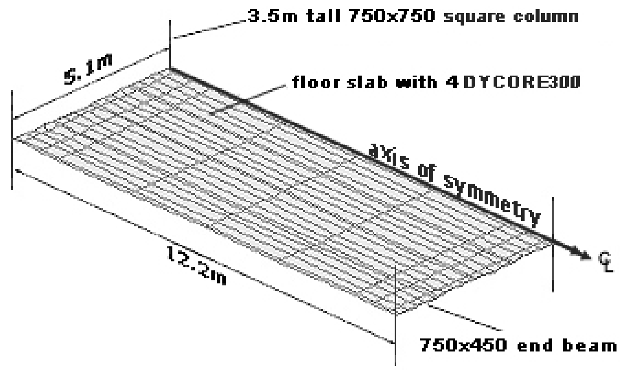

Figure 3: Dimensions and layout of the studied subassembly

3. SIMULATION MODEL

A new computational model was developed on the platform of SAFIR to simulate the structural behaviour of subassemblies with hollowcore floor systems under fire conditions. SAFIR is a non-linear finite element program performing both thermal and structural analyses [11], and it takes account of thermal and mechanical properties of concrete and steel at elevated temperatures following the Eurocodes [12, 13]. The program has been validated against many experimental results [14].

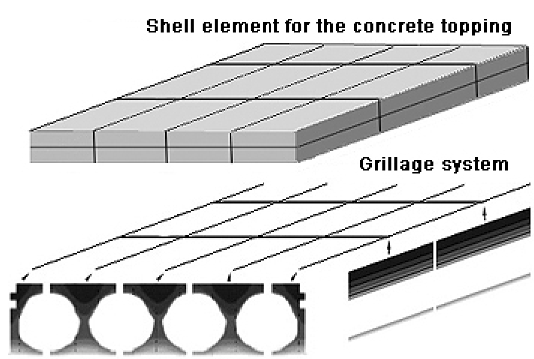

Figure 4: Discretisation method in the proposed model

The reinforced concrete topping slab is simulated using a layer of shell elements to take into account the continuity between the hollowcore units, and each hollowcore unit is simulated using a grillage of 3D beam elements. The longitudinal beams in the grillage can capture the prestressing effect and enable the thermal gradient in the web to be calculated accurately. The transverse beam elements running across the width of the hollowcore units simulate the thermal expansion and thermal bowing across each unit. This model, shown in Figure 4, has been validated against existing test results. Except for not being able to predict shear failures, the simulation results showed good agreement with the experiments [14].

Some details are overlooked in this model. Shear and anchorage failures, bond failures and vertical tensile stresses in the web are not captured due to the complexity and the computational effort needed when simulating the entire structure. However, a detailed study on the shear and anchorage behaviour of hollowcore concrete slabs has been carried out by Fellinger [9] and findings from that study are included in the design recommendations. Spalling is also not considered as the possibility of spalling depends on the curing period and the age of the building, and currently there are very few finite element structural analysis programs considering spalling due to the uncertainties and the lack of specific experimental data.

The simple end connection is translated into the SAFIR model as shown in Figure 5. The load path in the end connection is shown in Figure 5(a) and is modelled by three rigid elements connected to each other at the end of each line of beam elements as shown in Figure 5(b). The first rigid element (1), from the bottom of the hollowcore unit to the mid-height of the topping, transfers the vertical load from the end of the hollowcore units to the beam seating point. The second rigid element (2) represents the solid concrete between the seating and the node-line of the beam. The third rigid element (3) connects the shell elements on top of the beam to the node-line of the beam. As the ends of the hollowcore units are in full contact with the supporting beam, no relative displacement is allowed between these two surfaces.

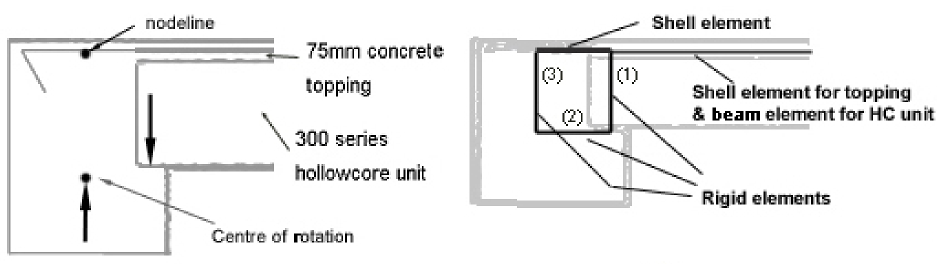

Figure 5: Modelling the simple and the non-gapping end connections (a) Node-line of the model in SAFIR and force paths in the connection (b) Simulation scheme in SAFIR

In the non-gapping end connection (Figure 1(c)) the reinforced concrete cell filling is included in the beam grillage which represents the hollowcore units, and the force path in this end connection is the same as in the simple end connection, as shown in Figure 5(b).

The modelling scheme of the gapping end connection (Figure 1(b)) is shown in Figure 6, which also uses three rigid elements at the ends of every line of beam elements representing the hollowcore units. The significant difference between the gapping and the simple end connection details is the soft packing at the ends of the hollowcore units which allows sliding displacement until the two surfaces press against each other. This connection is modelled in the same way as the simple end connection except for the junction between rigid elements (1) and (2), where horizontal sliding is permitted, as shown in Figure 6(b). To be strictly correct, in the gapping end connection the displacement of the bottom of the hollowcore units moving towards the face of the end beams should be limited to the size of the gap, but this limitation requires an artificial material in the model which currently cannot be included in SAFIR, and so it is ignored in the simulations.

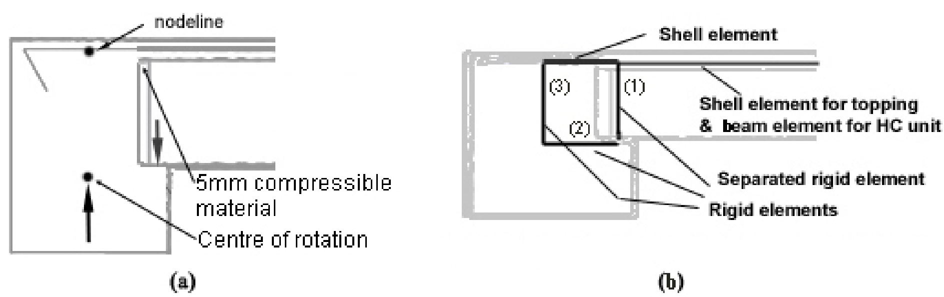

Figure 6: Modelling the gapping end connection (a) Node-line of the model in SAFIR and force paths in the connection (b) Simulation scheme in SAFIR

4. ANALYTICAL RESULTS

Table 1- Summary of the simulation results

End connection	Side connection	Simulation stop time	Reason
Simple	No infill	>240min.	Designated end time
Gapping		148min.	Numerical problem
Non-gapping		>240min.	Designated end time
Simple	Infill	187min.	Numerical problem
Gapping		60min.	Numerical problem
Non-gapping		181min.	Numerical problem
Simple	No side beams	123 min.	Crushing of topping near the ends
Gapping		51 min.	Numerical problem
Non-gapping		84 min.	Crushing of topping near the ends

Table 1 summarises the simulation results, and Figure 7 compares the maximum vertical displacement at the centre of the slab. It can be seen that many of the simulations were stopped due to numerical problems. Although SAFIR could not determine the failure mode of the slabs in fire in some simulations, the comparison of vertical displacement shows that the gapping end connection is the least favourable when considering the fire resistance of the subassembly.

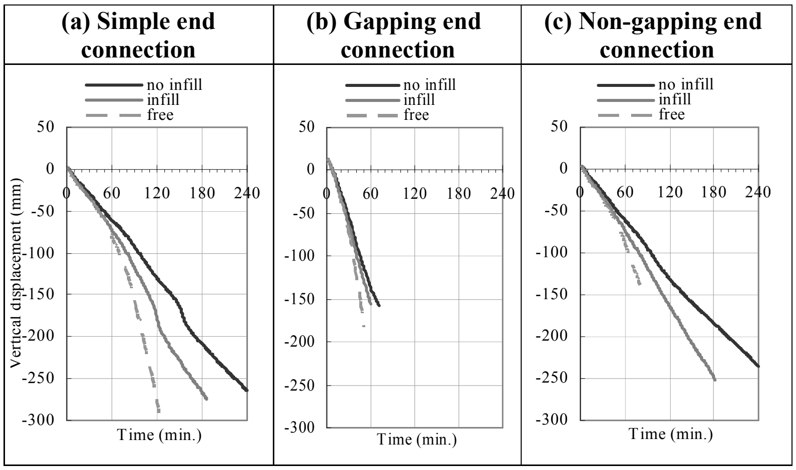

Figure 7: Maximum vertical displacement of the slabs with different end and side connections

A comparison of Figures 7(a) to (c) shows that the slabs with the simple end connection and the non-gapping end connection behave similarly to each other and exhibit a similar trend of vertical displacement. The slight difference between them is caused by the core-filling which only exists in the non-gapping end connection. The floor slab with the gapping end connection has a larger deflection and fails much earlier than with other types of end connection because the lack of rotational restraints at the ends prevents the arch action. Further investigation on the stress distribution within the cross section of the hollowcore slabs confirms this finding [15], where significantly lower compressive force near the ends is found in the slab with the gapping end connection than with other types of end connection. However, as the gap between the end of the hollowcore slab and the supporting beams could eventually be closed in reality, some arch action could still be achieved but at a time much later than in the slabs with the simple or the non-gapping end connections.

In terms of side connections, among the nine cases shown in Figure 7, the slabs with "no infill" side connection have the smallest deflection and the fire resistance is more than twice of that of the subassemblies without side beams. This is because of the development of two-way behaviour as tensile membrane action is established in the topping concrete. Previous studies on reinforced concrete slabs show that two-way behaviour can increase the load capacity via membrane effects to the level predicted by using yield line theory, and consequently increase the fire resistance [16, 17]. The "infill" lines on Figure 7 indicate that two-way behaviour is less effective with the cast in-situ infill at the side of the slab. This may be because the concrete infill allows larger deflection of the hollowcore unit closest to the side beams. Nevertheless, the difference between using "in fill" and "no infill" side connection is not significant, and both side supports are better than having no side supports because of the beneficial effect of two-way action. In practice this means the fire resistance of the slab can be increased by providing side beams or by adding extra "fire emergency beams" to slabs which have large number of hollowcore units side by side. The extent of this increase depends on the spacing of the "fire emergency beams" and the fixity between floor slab and the beams.

5. CONCLUSIONS

The results in the study show that the connections that are beneficial to seismic design are not always good for fire design; and it is important to find the balancing point. In terms of the fire performance of hollowcore floor systems, rigid connections at both the ends and the sides of the floor systems to the supporting beams provide better fire resistance than rotationally flexible connections. The simulation shows that any kind of gap between the end of the hollowcore units and the end beams will reduce the axial restraint, and hence give larger deflection during fire and decrease the fire resistance. Fellinger [9] pointed out that hollowcore concrete flooring systems without axial restraint are also more likely to have shear and anchorage failures in the early stages of the fire. Therefore, the gapping end connection is not good for the overall structural performance of the hollowcore floor system in fire. This conclusion is based on a model which ignores the possibility of axial restraint after closure of the gap between the hollowcore units and the end beams, so a more sophisticated model is needed for a more definite conclusion to be drawn.

In terms of the connections between the hollowcore units and the parallel side beams, a rigid side connection with the hollowcore units placed immediately adjacent to the side beams has better fire resistance than a flexible side connection with infill concrete, and further investigations show that this effect is more significant with long spans or high load ratios. Nevertheless, this type of side connection conflicts with the recommendation of seismic design. Because the difference between the fire performance of the slab with infill and no-infill side connections is not significant, the infill side connection is recommended considering both fire and seismic effects.

To maximise the performance of the hollowcore floor systems in fire and earthquakes, it is recommended to use rigid non-gapping end connections as shown in Figure 1(c) and rotationally flexible side connections as shown in Figure 2(b).

5. ACKNOWLEDGEMENTS

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